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Lightweight metal laminated plates produced via (hot, cold and cryogenic) roll bonding: A review

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Abstract: Due to the comprehensive advantages of various metals, metal laminates have been paid much attention. Roll bonding method has become one of the main fabrication methods of metal laminates, benefiting from the advantages of stable and continuous production. The research progress in the roll bonding of metal laminates is reviewed, mainly including the hot roll bonding, cold roll bonding, accumulative roll bonding and cryogenic roll bonding. The formation mechanism of bonding interface and the main influence factors on the interfacial bonding quality are systematically discussed. Moreover, further prospects are pointed out on the advancement of high-performance roll bonding of metal laminates.

Key words: metal laminates; roll bonding; bonding interface; mechanical property

1 Introduction

With the rapid development of science and technology, many new requirements for metallic materials are put forward, such as low density, high strength, high wear resistance and corrosion resistance. Under this situation, the unitary metallic material is difficult to meet the needs of industrial production and metallic lamellar composites come into being, which have attracted much attention because of their unique physical and chemical properties [1]. There are many species of metal laminates [2−5], including Cu/Al, Mg/Al, Al/steel, Cu/invar, etc. They have been widely applied in the fields of automobile, aviation, shipbuilding, electronics and chemical industry, such as heat exchanger for automobile [6], aircraft parts [7], ship hull [8], electronic components [9], and grounding wire for petrochemical enterprises [10]. The promotion and application of metal laminates are of great significance to solve the outstanding problems of current energy structure and industrial structure [11].

Currently, the preparation technologies of metal laminates have made great progress, which can be divided as liquid−liquid bonding, solid−liquid bonding and solid−solid bonding according to the physical state of matrix metal. The typical liquid−liquid bonding method is the core filling continuous casting technique. In the fabrication process of metal laminates, the solidification of matrix metal and formation of bonding interface can be simultaneously carried out, which obviously shortens the production process [12]. Nevertheless, core filling continuous casting technique demands very high control precision on the process variables and exhibits low yield of finial products [13].

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Roll-casting technique is regarded as the representative of solid−liquid bonding of metal laminates [14]. Compared with the core filling continuous casting technique, the obvious advantages of roll-casting technique are high production efficiency and low production costs. Moreover, high interfacial bonding strength can be easily obtained under the dual effect of high temperature and rolling pressure [15]. However, the high temperature of liquid metal from another perspective, also leads to the high energy consumption.

Nowadays, the solid−solid method is used for the widest range of the industrial application due to its process controllability, which mainly includes roll bonding technique [16], extrusion bonding technique [17], and explosive welding technique [18]. Compared with other techniques, the less pollution, stable production process and high production efficiency of roll bonding technique make obvious advantages. In the roll bonding process, the oxidation film on the surface of matrix metal is broken and obvious plastic flow occurs under the action of huge rolling pressure. And then, close contact for these atoms around the bonding interface is carried out. Finally, metallurgical bonding interface is formed through the heat input and atomic diffusion. Before roll bonding, surface treatment is usually adopted to remove the grease or dirt and expose the fresh matrix metal. Moreover, the annealing process is also necessary to regulate the thickness of intermetallic compound layer [19].

In this work, the recent efforts and advances in the roll bonding of metal laminates are reviewed to reveal the potential mechanism. Based on the comprehensive understanding and our numerous original works, some important issues about the fabrication method, evolution mechanism of bonding interface and reinforcement factors of roll-bonded metal laminates are discussed and emphasized. Finally, some prospective viewpoints about the design, fabrication and fracture mechanism of roll-bonded metal laminates are proposed for future work.

2 Roll bonding techniques for metal laminate plates

2.1 Hot roll bonding technique

The hot roll bonding technique of metal laminates initially appeared in the 1940s, which was widely applied in the fabrication of thick plate. The hot roll bonding technique can reduce the rolling force but with weak production stability. Before hot roll bonding, matrix metals are preheated to a certain temperature, which will significantly affect the comprehensive properties of metal laminates. Low preheated temperature may lead to the high resistance to deformation and insufficient atomic diffusion around the bonding interface [20]. Nevertheless, the formation of the thick intermetallic compound layer, even the interfacial cracks, is easily induced by the high preheated temperature [21]. Moreover, protective atmosphere is generally adopted in the hot roll bonding process to avoid the oxidation of interfacial metal [22,23], as shown in Fig. 1.

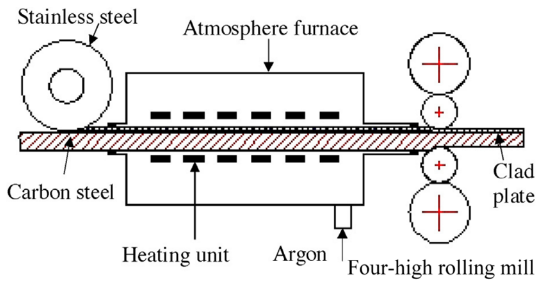


Fig. 1 Schematic diagram of hot roll bonding system [22]

Numerous works about hot roll bonding of metal laminates have been carried out. MENON and CHEN [24] used hot rolling and annealing to fabricate crack-free laminate composites of Al_2O_3 and ZrO_2 with a layer thickness of 4−60 μm. Ag/Cu bimetallic laminate sheets were fabricated by roll bonding at different temperatures and annealing for different periods at 673 and 1073 K by ZHANG et al [25]. They found that the speed of Cu atoms moving into the Ag side was faster than that of Ag atoms moving into Cu side. PENG et al [26] fabricated Cu/Al laminate by hot roll bonding at 430 °C with a reduction of 60% in a single pass. At lower sintering temperature, $CuAl_2$ appeared at the interface. As the temperature increased, Cu_9Al_4 phase increased. LUO et al [27] found that the growth rate of intermetallic compounds (IMCs) at the bonding interface of the hot-rolled Al/Mg laminate increased with the increase of the annealing temperature, and the mathematical relationship among the IMCs thickness (y, μm), annealing temperature (T, K) and annealing time (t, min) was built as

$$y^2 = 1.98\times10^6 \exp(-\frac{83418}{RT})(t-0.78\exp\frac{29770}{RT}) \quad (1)$$

where R is the molar gas constant (8.314 J/(mol·K)). CUI et al [28] thought that roll bonding and subsequent reaction annealing of Ti/(TiB_2/Al) laminate sheets were a feasible near-net-shape processing method for the production of TiAl matrix composite sheets, as shown in Fig. 2.

2.2 Cold roll bonding technique

Different from the hot roll bonding technique, cold roll bonding process is completed at room temperature. Moreover, more than 60% reduction in the first rolling pass accompanied by the high-level equipment is necessary to obtain the high bonding quality [29]. The significant advantages of cold roll bonding techniques are that the flexible regulation of IMCs thickness can be easily achieved through adjusting the annealing process and the oxidation of matrix around the bonding interface is avoided. From another perspective, serious edge cracks may appear in the metal laminates with hard and brittle matrix metals [30,31]. In our previous research [32], we found that cold rolling processing could further improve the bonding strength of Al/steel clad sheet fabricated by horizontal twin-roll casting. Moreover, the annealing effect on the microstructure and mechanical properties of Al/Ti/Al laminate sheets fabricated by cold rolling was investigated [33]. Interestingly, a new kind of trimodal material, consisting of a combination of coarse-grained Al, ultrafine-grained Ti and $TiAl_3$ particles was produced, which showed the highest yield strength and good ductility, as shown in Fig. 3. Meanwhile, the specific diffusion coefficient (D) for the Ti−Al system was proposed by LUO and ACOFF [34], which was expressed as

$$D = -\frac{1}{2t}\left[\frac{\partial N_A}{\partial x}\right]^{-1}\int_{N_{A1}}^{N_A} x\,\mathrm{d}N_A \quad (2)$$

where N_A represents the composition or atomic fraction at a distance x from the Matno interface, N_{A1} represents the concentration of one side on the diffusion couple at a point away from the interface where the composition is constant, $[\partial N_A/\partial x]^{-1}$ represents the inverse of the concentration gradient, and $\int_{N_{A1}}^{N_A} x\,\mathrm{d}N_A$ represents the integral.

HWANG et al [35] studied the influence of period of heat treatment at 723 K on the mechanical properties and microstructure of cold rolled Al/stainless steel laminate. They found that the bonding strength for cold-rolled laminate was resulted from mechanical locking, while the bonding strength reached the maximum when annealing at 723 K for 1 h due to solid-solution strengthening effect. YANG et al [36] used diffusion bonding and cold rolling to improve the bonding quality of Mo/Cu laminate sheets which had high thermal conductivity and low coefficient of thermal expansion. The Mo/Cu laminate sheets have potential application in electrical contacts, and electroerosion segments for hart metals. Three brazed A4343/A43003/A4343 laminate sheets were cold rolled with reduction of 17%, 22% and 44% by KIM et al [37]. They found that the core of the samples with reduction of 17% and 22% kept a deformed microstructure, whereas the microstructure of the brazed cold-rolled sample with reduction of

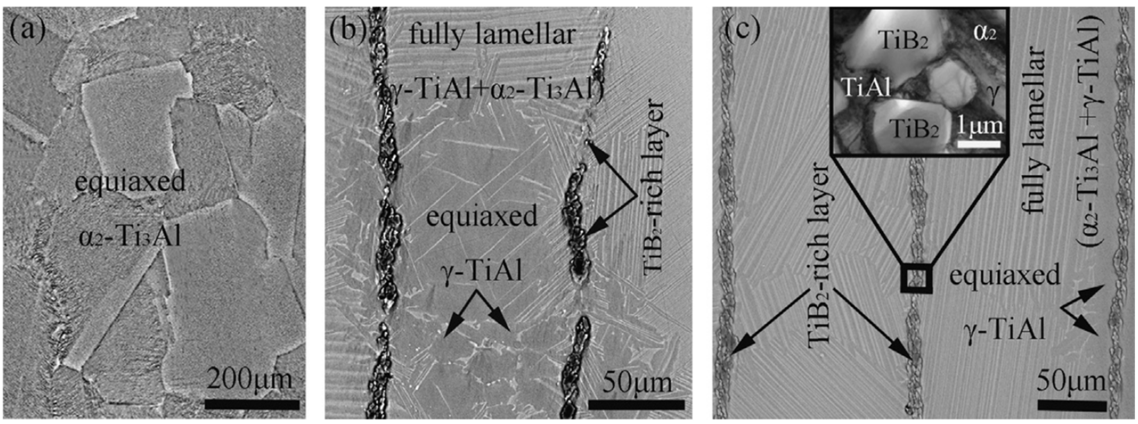


Fig. 2 Morphologies of different TiAl matrix composites: (a) Monolithic Ti_3Al; (b) TiB_2(L)−TiAl; (c) TiB_2(H)−TiAl [28]

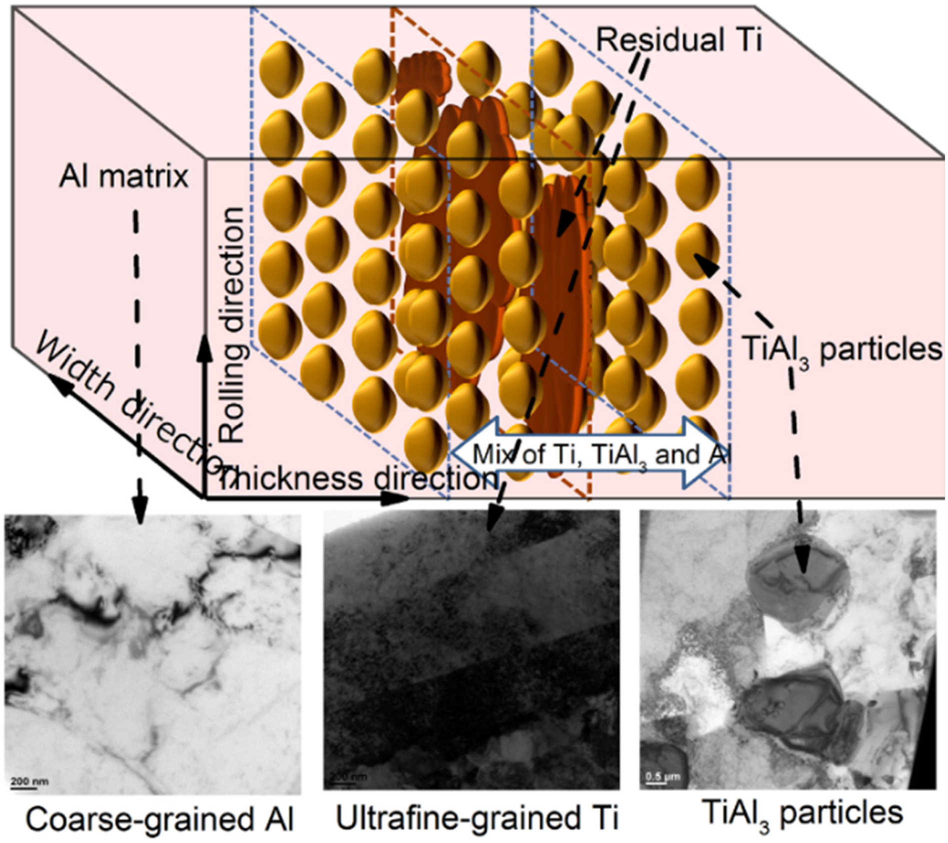


Fig. 3 Illustration of new trimodal sheets combined with coarse aluminium matrix, nanograined Ti and $TiAl_3$ particles [33]

44% was composed of coarse elongated grains. SHENG et al [38] found that low temperature heat treatment can improve the interfacial bonding quality of cold-roll bonded Cu/Al/Cu laminate sheets. However, high temperature heat treatment will lead to Al_2Cu intermetallic layer, which decreased the bonding strength of laminate sheets, as shown in Fig. 4.

2.3 Accumulative roll bonding technique

Accumulative rolling bonding (ARB) technique was proposed by SAITO et al in 1998 [39], which was applied in the fabrication of metal laminates with ultra-fine grain structure and consisted of a repeated sequence of sectioning, cleaning, stacking, and roll bonding [40], as shown in Fig. 5. In the previous research [41], we developed a new technique to produce ultra-thin bimetallic foils, which combined the features of ARB and asymmetric rolling. After the third asymmetric rolling pass, the grain size was about 140 nm for the AA6061 layer and 235 nm for the AA1050 layer. On this base, YU et al [42] found that the equivalent strain was the greatest at a rolling speed ratio of 1.2, leading to a uniform strain distribution and a stronger bond. Furthermore, an extended ARB technique, called the “four-layer ARB”, was developed. And the bonding strength of clad sheets processed by the “four-layer ARB” was 2−2.2 times greater than that by the traditional ARB technique [43].

The feasibility of the fabrication of the nanostructured Cu/Al/Ag multi-layered composites by ARB was evaluated by SEIFOLLAHZADEH et al [44]. More importantly, a theoretical model to predict the tensile strength of the composites was developed using strengthening mechanisms and some structural parameters extracted from XRD. ANGHELUS et al [45] used ARB technique to fabricate Al-based laminate sheets reinforced by an Al−Ni−Sn metallic glass forming alloy. This kind of laminate showed stable nano or ultrafine grained microstructure. Bulk Cu/Ta nanolamellar multilayers were successfully fabricated by ZENG et al [46] via the cross ARB technique, which could effectively suppress the formation of plastic instabilities and edge cracks during the repeated

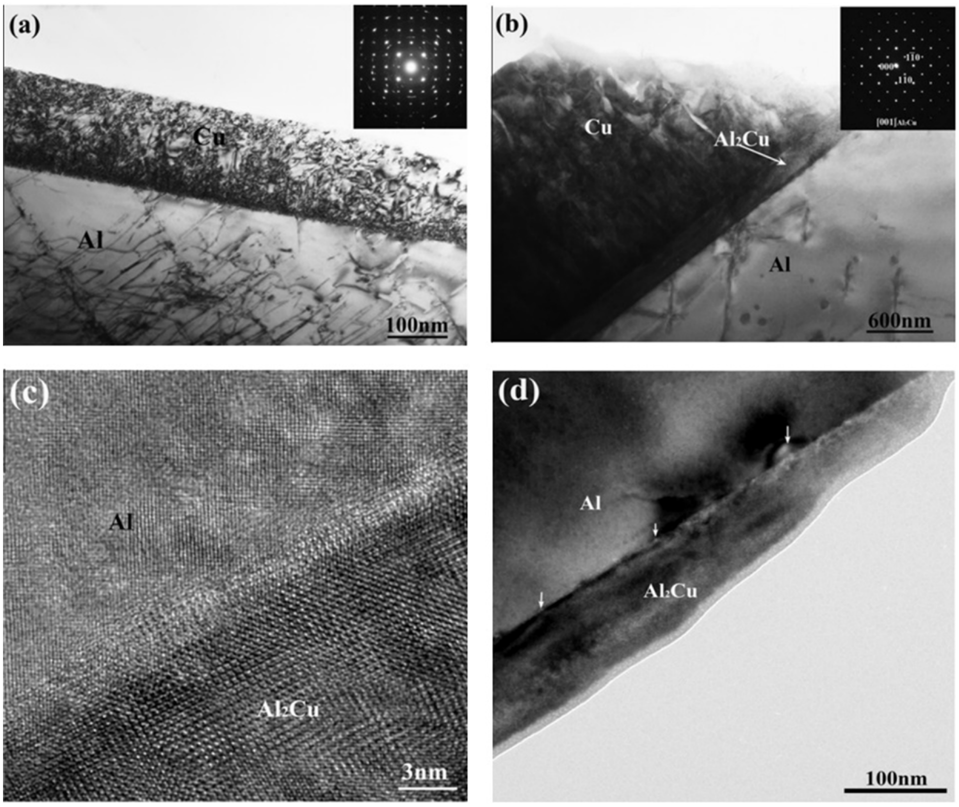


Fig. 4 (a) Bright field TEM image of Cu/Al interface of clad sheet with 423 K, 1 h treatment; (b) Formation of Al_2Cu layer along Cu/Al interface after 423 K, 20 h treatment; (c) HRTEM image of Al_2Cu with electron beam parallel to [001] direction; (d) Precipitates of Al_2O_3 along Al/Al_2Cu interface in clad sheet with 573 K, 10 h treatment (as the arrow pointed) [38]

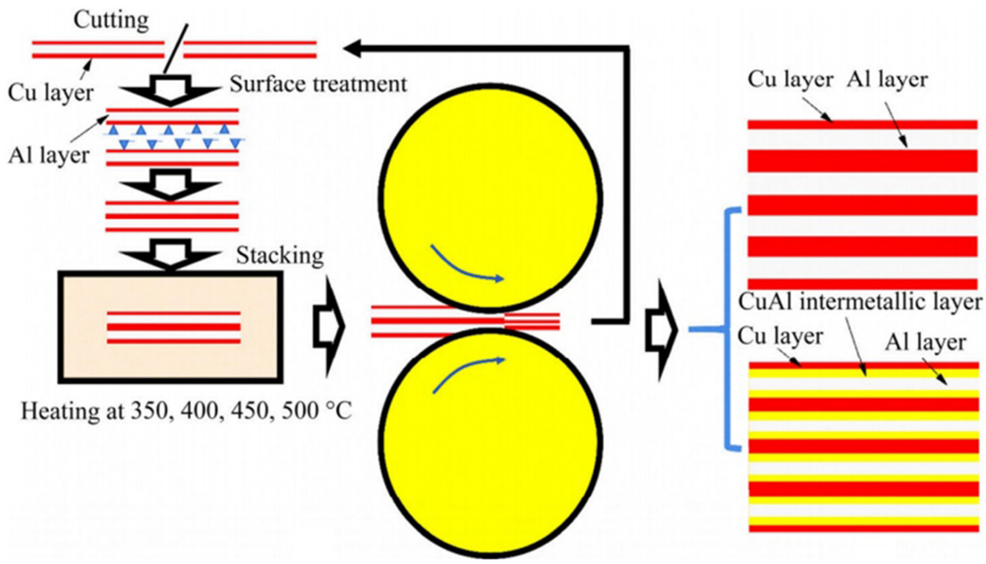


Fig. 5 Schematic illustration of cross accumulative rolling bonding process [40]

rolling process. JAFARIAN et al [47] found that the ultimate tensile strength and elongation of Al/Cu/Zn/Ni multi-layered composite fabricated by ARB gradually increased with the increase of the number of ARB cycles, which was beneficial from the good bonding between the layers and the uniform distribution of the reinforced layers within the matrix phase. To explore correlation between micromechanical behavior and mechanical properties of multilayered Ti/Nb composites processed by ARB, in-situ high-energy X-ray diffraction tensile tests were performed by JIANG et al [48]. GAO et al [49] fabricated a hierarchical Cu/Nb laminate composite with high strength, sufficient ductility, super- conductivity and superior helium irradiation via the coded ARB, as shown in Fig. 6. In their work, the final maximum equivalent strain (ε) was as high as 14.3 in both the thinnest Cu and Nb layers calculated by Eq. (3):

$$\varepsilon=\frac{2}{\sqrt{3}}\ln(H_0/h) \tag{3}$$

where H_0 and h represent the initial and final layer thickness, respectively.

2.4 Cryogenic roll bonding technique

Cryogenic roll bonding technique is an emerging technology to fabricate metal laminates, which can significantly improve overall performance of composite strip [50]. The microstructure, texture and mechanical properties of the AA1060 aluminum alloy sheets processed by ARB at cryogenic temperature were investigated by WANG et al [51]. DU et al [52] indicated that the subsequent cryorolling could further refine the grains in the ARB-processed AA1060 sheets. TAKAGAWA et al [53] successfully improved the tensile properties of the Cu−2.0wt.%Ni−0.5wt.%Si−0.1wt.%Zr alloy without reducing its electrical conductivity by combining both ARB and cryorolling with aging treatment. YU et al [54] found that the edge cracks appeared in the cold roll bonding of Al/Ti/Al laminate sheets could be avoid by the cryogenic roll bonding process, as shown in Fig. 7. Furthermore, the ultimate tensile stress of laminate sheets by cryogenic roll bonding increased up to 36.7% compared to that by cold roll bonding. On this foundation, the bonding strength of Al/Ti/Al laminated composites fabricated by the cryorolling, cold rolling and hot rolling was compared by LIU

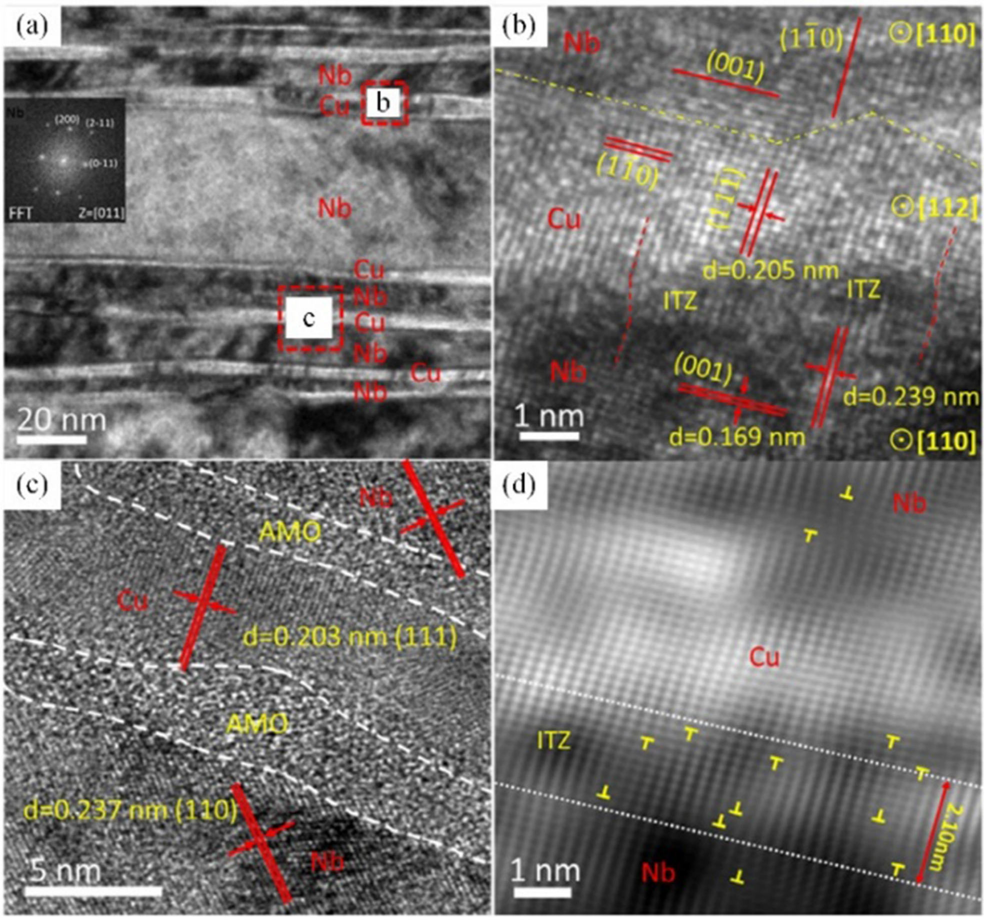


Fig. 6 Low magnification image of typical morphology of intermixing interfaces and adjacent layers (a) and corresponding enlargement, showing interfacial transition zone (ITZ) (b) and amorphous (AMO) (c) interface, respectively, and corresponding IFFT image (d) [49]

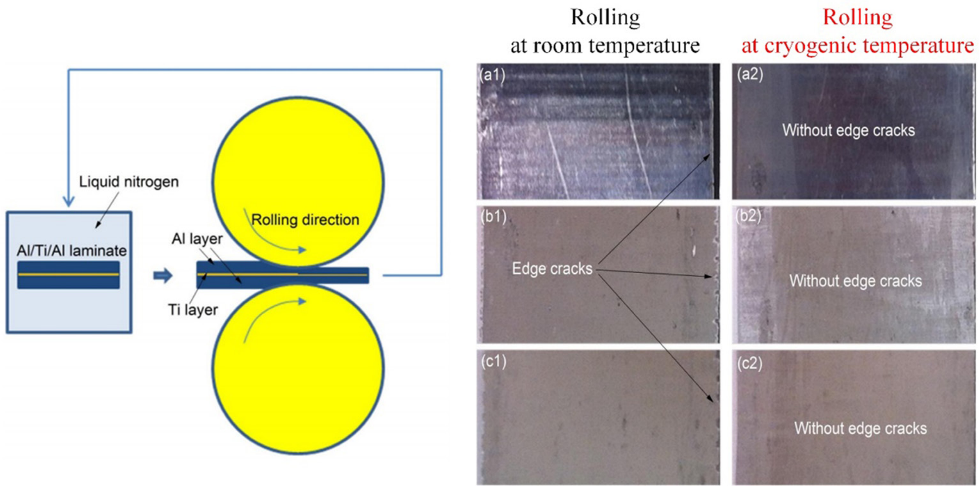


Fig. 7 Schematic diagram of cryorolling process and morphology of Al/Ti/Al clad sheet [54]

et al [55]. They thought that the enhanced bonding strength of Al/Ti/Al laminated composites via cryorolling depended on the mechanical locking strength, metallurgical bonding strength, and tensile strength of the Al layer.

The microstructure evolution and mechanical performance of Cu/Al/Cu clad sheets fabricated by hot rolling, cold rolling and cryorolling were compared by WANG et al [56]. Results revealed that the highest ultimate tensile strength and the best ductility of the composites were achieved by cryorolling at −100 °C. Compared with the room temperature rolling process, the increment of yield strength ($\Delta\sigma_{\mathrm{Y}}$) for AA3003 sheets in the cryogenic rolling process was characterized as [57]

$$\Delta\sigma_{\mathrm{Y}} = \Delta\sigma_{\mathrm{P}} + \Delta\sigma_{\mathrm{dis}} + \Delta\sigma_{\mathrm{gb}} \tag{4}$$

where $\Delta\sigma_{\mathrm{P}}$, $\Delta\sigma_{\mathrm{dis}}$, and $\Delta\sigma_{\mathrm{gb}}$ are the strengthening increments in the yield strength between the cryorolling and room temperature rolling conditions resulted from the precipitation strengthening, dislocation strengthening, and grain refinement strengthening, respectively.

2.5 Other roll bonding techniques

In addition to the above techniques, there are still many other meaningful roll bonding methods to fabricate the metal laminates, which have their own application range and certain advantages. For the dissimilar metals with significant difference in the mechanical properties, different temperature roll bonding techniques could effectively coordinate the plastic deformation of dissimilar metals [58]. Compared with the symmetric roll bonding, asymmetrical roll bonding technique can reduce the rolling force and improve the bonding quality of metal laminates, benefiting from the formation of cross-shear zone [59]. Accumulative extrusion bonding technique was more effective than the conventional ARB technique in refining grain and improving mechanical properties of specimens [60]. Pack roll bonding technique can not only avoid the interfacial oxidation in the hot roll bonding process but also solve the problem of interfacial cracking [61]. Pulse current assisted roll bonding technique exhibited the obvious advantages of promoting the atomic diffusion at the bonding interface, improving the interfacial bonding strength and inhibiting the edge cracks [62]. Directing against the bottle necked problem of the low interfacial bonding strength, weak flatness and large residual stress in the fabrication of metal laminates, the corrugated-flat rolling technique was developed [63].

3 Mechanism of interface bonding of roll-bonded metal laminates

3.1 Roll bonding theories

The investigation of the formation mechanism of bonding interface is crucial to improving the bonding quality of roll-bonded metal laminates, which attracted the attention of the researchers around the world. Meanwhile, some famous roll bonding theories of metal laminates have been proposed. The mechanic joggle theory was built by BOWDEN and TABOR [64]. In the roll bonding process, corrugated interfaces were smoothly geared under the action of rolling pressure, achieving the mechanic joggle of dissimilar metals. Nevertheless, DING and ZHANG [65] thought that the formation of bonding interface was induced by the chemical bonding reaction of dissimilar metal atoms and thus the metallic bond theory was developed. On the base of the metallic bond theory, the energy theory was proposed by MOHAMED and WASHBURN [66]. The key idea of this theory was that only the spacing between activated atoms was small enough, which could achieve the bonding of dissimilar metals. Similarly, diffusion theory was put forward by MITANI et al [67]. It was thought that interfacial atoms were activated by the input energy from the roll bonding process and inter-diffused to form the diffusion layer [67]. There are still some similar theories about the formation mechanism of bonding interface of roll-bonded metal laminates, such as thin film theory [68], crack healing theory [69] and recrystallization theory [70], which will be not elaborated here.

The above roll bonding theories considered the formation of bonding interface as a single process, which is actually a gradual process. Under the concerted effort of numerous scholars, the famous three-stage theory was suggested, including the physical contact stage, physicochemical reaction stage and inter-diffusion stage [71]. Afterward, the three-stage theory was modified as Bay theory [72]. It was widely recognized and divided the roll bonding process as four stages. Firstly, oxidation film and work hardening layer are broken under the huge rolling pressure. Secondly, the expansion of broken surface makes the matrix metal exposed. Thirdly, matrix metals are squeezed into the cracks in the oxidation film and work hardening layer. Finally, dissimilar metal atoms at the bonding interface are activated to form the metallurgical bonding. The dissimilar metal bonding process of Bay theory [73] is provided as Fig. 8. These roll bonding theories have their own characteristics, but still need to be further explored to perfectly explain the interfacial bonding mechanism of metal laminates.

3.2 Interface evolution mechanism of roll-bonded metal laminates

To obtain the sophisticated understanding of formation mechanism of dissimilar metal interface, numerous investigations about the interface evolution law of roll-bonded metal laminates have been carried out. To clarify the deformation behavior and fracture forms of Ti/Al/Mg/Al/Ti laminates, in-situ bending and stretching tests were conducted on the hot-rolled and annealed composites, with a focus on crack initiation and propagation of the intermetallics and component layers [74]. Highly borated austenitic stainless steel thick plates with enhanced ductility and toughness using a hot-roll-bonding method were fabricated and the hot-roll-bonding mechanism was clarified by LI et al [75], as shown in Fig. 9. In the initial state, the bonding interface was divided as austenite/austenite and borides/borides regions. As the total rolling compression ratio was increased, the bonding interface was preliminarily formed in

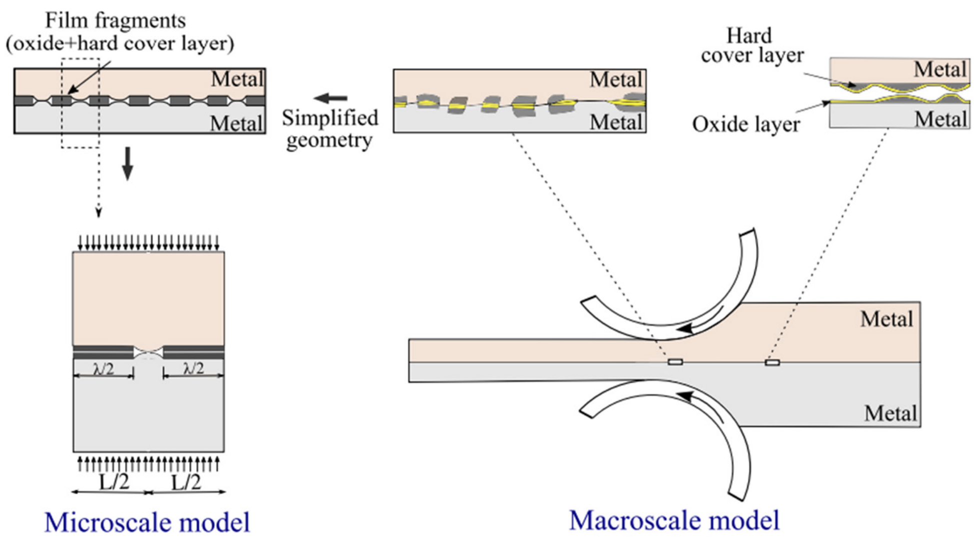


Fig. 8 Schematic diagram of dissimilar metal bonding process of Bay theory [73]

the austenite/austenite regions and new equiaxed grains owing to the austenite recrystallizaiton during the hot-roll-bonding could be observed at the bonding interface. As to the brittle borides/borides regions, they were firstly broken [76] and then surrounded by the plastically flowed austenite, leading to the thin diffusion layers formation between the $(Cr,Fe)_2B$ particles and austenite matrix. Finally, the metallurgy bonding interface containing the brittle ceramic particles was formed for the composite plates.

The interfacial formation mechanism of cold roll-bonded metal laminates is different from that of hot roll-bonded composite strip. WU et al [77] studied the bonding strength of Al/steel laminate after cold roll bonding and the bonding mechanism between layers was illustrated in Fig. 10. To modify the limited brittle layer formed by wire brushing process [78], a homogeneous surface hardened layer was formed by the nitriding treatment on the steel (Fig. 10(a)). In the initial stage of the cold roll bonding process, the depth and the number of cracks increased with the rolling pressure (Fig. 10(b)). As the thickness reduction kept increasing, aluminum was squeezed into the small gapes [79] and bonded with fresh steel matrix (Fig. 10(c)). Finally, some big and deep gapes were developed, which can further increase the bond area and the bonding strength (Fig. 10(d)).

Compared with the hot roll bonding technique and cold roll bonding technique, the plastic strain for ARB process in each rolling pass is much larger, accompanied by the unique interfacial evolution law [80]. The microstructural evolution and tensile properties of accumulative roll bonding of aluminum alloys 2219/5086 laminates were investigated by ROY et al [81]. The interfacial microstructure evolution is illustrated in Fig. 11. In the first four rolling passes, the strength increased due to the fact that strain hardening of AA5086 layers could be mitigated by intermediate annealing [82], and the two alloy layers maintained the starting minute strength difference at the beginning state, which helped maintain the iso-strain condition and straight interface (Fig. 11(a)). After the 4th rolling pass (the 5th and 6th passes), the stain-hardened AA5086 layer in localized regions could not be removed by the

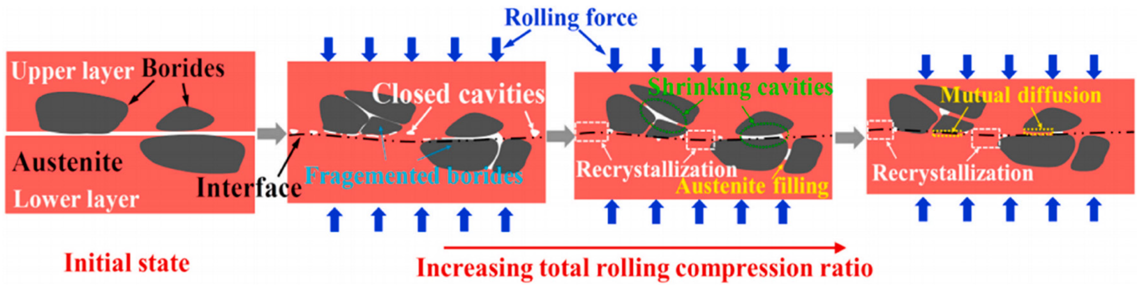


Fig. 9 Schematic diagrams of bonding mechanism in Al/nitrided steel clad sheet by hot roll bonding process [75]

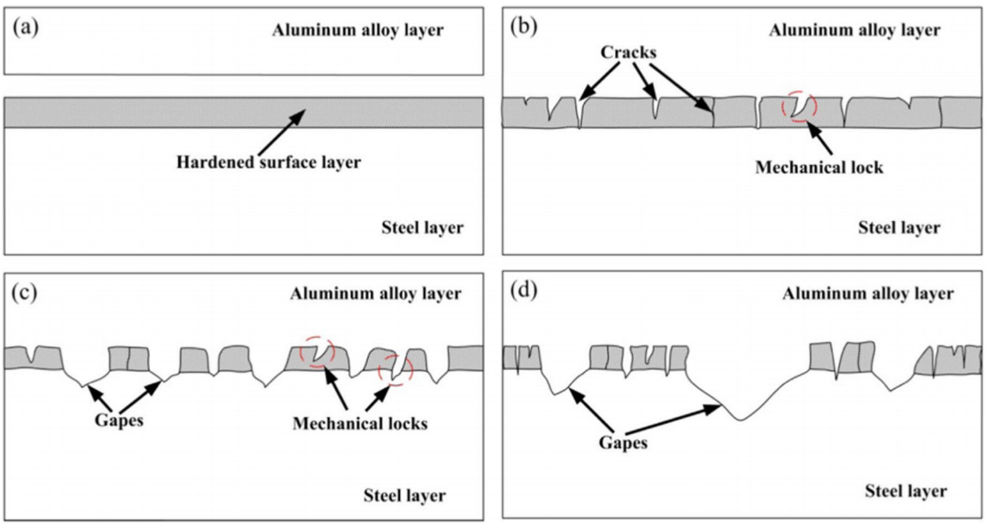
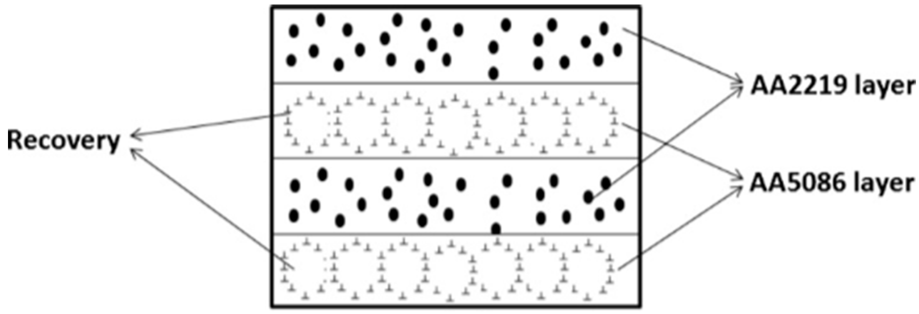
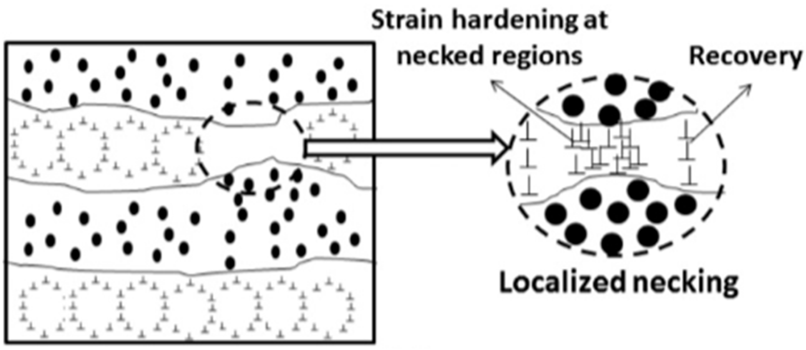


Fig. 10 Schematic diagrams of bonding mechanism in Al/nitrided steel clad sheet by cold roll bonding process [77]



(a)



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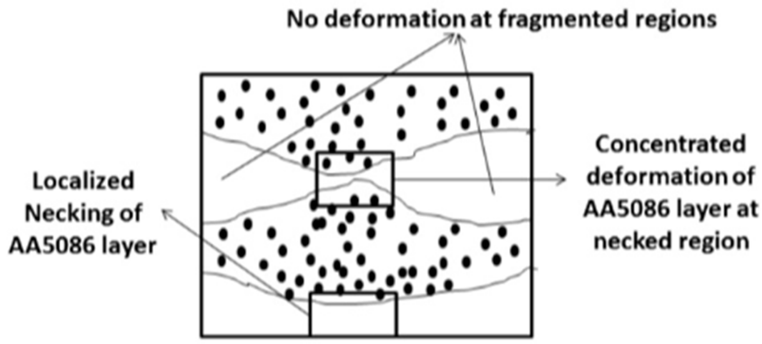

(c)

Fig. 11 Schematic diagram of microstructure development of aluminum alloys 2219/5086 laminates fabricated by accumulative roll bonding technique: (a) First four passes; (b) 5th and 6th passes; (c) 7th and 8th passes [81]

intermediate annealing, which caused the occurrence of necking (Fig. 11(b)). As ARB cycles were increased to the 7th and 8th passes, the deformation was concentrated at the necked regions, leading to the fragmentation of AA5086 layers and breakage of iso-strain condition (Fig. 11(c)).

As a newly emerging roll bonding method, cryogenic roll bonding technique has aroused the widespread concern, as well as the interfacial evolution law of cryogenic roll bonded metal laminates. YU et al [54] indicated that the mechanical performance of Al/Ti/Al laminate sheets could be enhanced through cryogenic roll bonding technique. Moreover, the difference of interfacial evolution mechanism of Al/Ti/Al sheets fabricated by the room-temperature roll bonding and cryogenic roll bonding was compared, as shown in Fig. 12. Before roll bonding, the Al and Ti plates with coarse grains were separated (Fig. 12(a)). In the rolling process, the grains around the bonding interface were significantly refined by the shear deformation, which was induced by the plastic difference between Al and Ti matrix. Compared with room-temperature roll bonding, cryorolling was more conducive to grain refinement (Figs. 12(b) and (d)) due to the suppression of the dynamic recovery behavior at cryogenic temperature [83]. With the further increase in the thickness reduction, fresh metal was exposed and ultrafine/nano grains began to accumulate at the bonding interface, which significantly facilitated the interfacial bonding. Furthermore, there were more interfacial junction

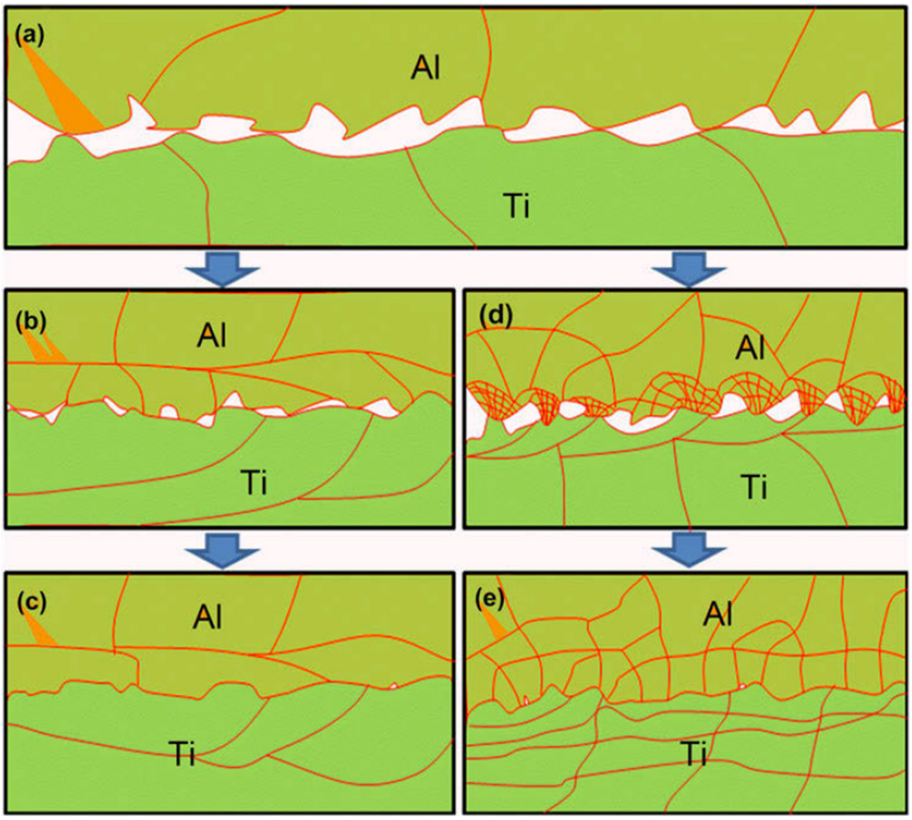

Fig. 12 Illustration of interface bonding during rolling: (a) Before rolling; (b, c) Interface with higher reduction by room-temperature roll bonding; (d, e) Interface with higher reduction by cryogenic roll bonding [54]

points, due to the smaller size of grains, for the laminate sheets fabricated by the cryorolling, resulting in the larger bonding strength.

4 Main factors for performance improvement of roll-bonded metal laminates

4.1 Suitable heat treatment and rolling process parameters

Numerous studies indicated that heat treatment and roll bonding parameters had the significant impact on the interfacial microstructure and mechanical performance of metal laminates. POZUELO et al [84] found that the heavy reduction ratio at low temperature (873 K) for a ten-layer UHCS-1.3C/MS laminate sheets had strong and microstructural perfect bond. PENG et al [85] studied the bonding strength and interface quality of Cu/Al metal laminates during hot rolling at rolling temperatures of 623, 703 and 773 K. When the rolling temperature was 703 K, they achieved the maximum bonding strength. Upper bound theorem and finite element method were used to simulate bimetal laminate rolling process by MALEKI et al [86]. They validated that the increase in reduction ratio would lead to higher bond strength. LIU et al [55] indicated that the interfacial bonding strength of Al/Ti/Al laminated composites fabricated through the cryorolling was higher than that by cold rolling and hot rolling. The influence of annealing temperature on the interfacial microstructure and peeling strength of Cu/Al clad sheet was studied by MAO et al [87]. The experimental results exhibited that the intermetallic compound layer thickness could be controlled within 550 nm after annealing at 250 °C and the peeling strength could reach 39 N/mm. Nevertheless, high-temperature annealing treatment led to the appearance of cleavage fractures and the sharp decrease in the bonding strength. In our previous research, the effect of interfacial microstructure regulated by the intermediate annealing process on the mechanical performance of Cu/Al/Cu clad sheet was explored. Experimental results verified that refining the interfacial grain indeed could improve the comprehensive performance of metal laminates [88], as shown in Fig. 13. In the fabrication process of Cu/steel clad sheet, similar conclusions were obtained [89].

4.2 Adding interlayer metal

LEE et al [90] reported that, due to the strong chemical affinity between matrix metals, inter-metallic compounds formed readily at the bonding interface during the heat treatment process are difficult to regulate, resulting in decrease in bonding strength that limits the efficacy of material. As such, a considerable amount of recent research has aimed towards the introduction of an effective interlayer that can enhance bonding of roll-bonded metal laminates [91]. The effect of Ni interlayer on the interfacial microstructure and mechanical performance of Cu/Al clad sheet was investigated by KIM and HONG [92]. The experimental results showed that the addition of Ni interlayer could optimize the crack propagation path to improve the interfacial bonding strength of Cu/Al clad sheet, which was also proved by GAO et al [93], as shown in Fig. 14. YAN et al [94] indicated that the addition of nickel interlayer could significantly improve the tensile shear strength of titanium alloy/stainless steel clad strip fabricated by the vacuum hot roll bonding. Similarly, LUO et al [95] demonstrated that the interfaces were free from cracks and discontinuity, and interdiffusion between the stainless steel and the titanium was effectively prevented by inserting a layer of pure Nb foil. Based on the diffusion welding technique, Mg/Al clad sheets with a Cu interlayer was prepared by VARMAZYAR and KHODAEI [96]. The Mg/Al clad sheets with the rolled Cu foil interlayer exhibited the higher interfacial bonding strength than those with annealed Cu foil interlayer, due to the larger interfacial contact area.

In addition, numerous research has been carried out through the first-principles calculation to explain the enhancement mechanism of metal interlayer on the metal laminates. The promotion mechanism of alloy elements on the formation of high-strength covalent bond was elaborated through the first-principles calculation by PENG et al [97] and WANG et al [98], as shown in Fig. 15. Furthermore, YUAN et al [99] indicated that the precipitation of α-Al(Fe,Mn)Si particles at the bonding interface could significantly improve the corrosion resistance of Al alloy clad sheets. Based on the first-principles calculation, CZELEJ and KURZYDŁOWSKI [100] found that the addition of C and Mg element benefitted the improvement of interfacial bonding strength of steel/Al clad sheet.

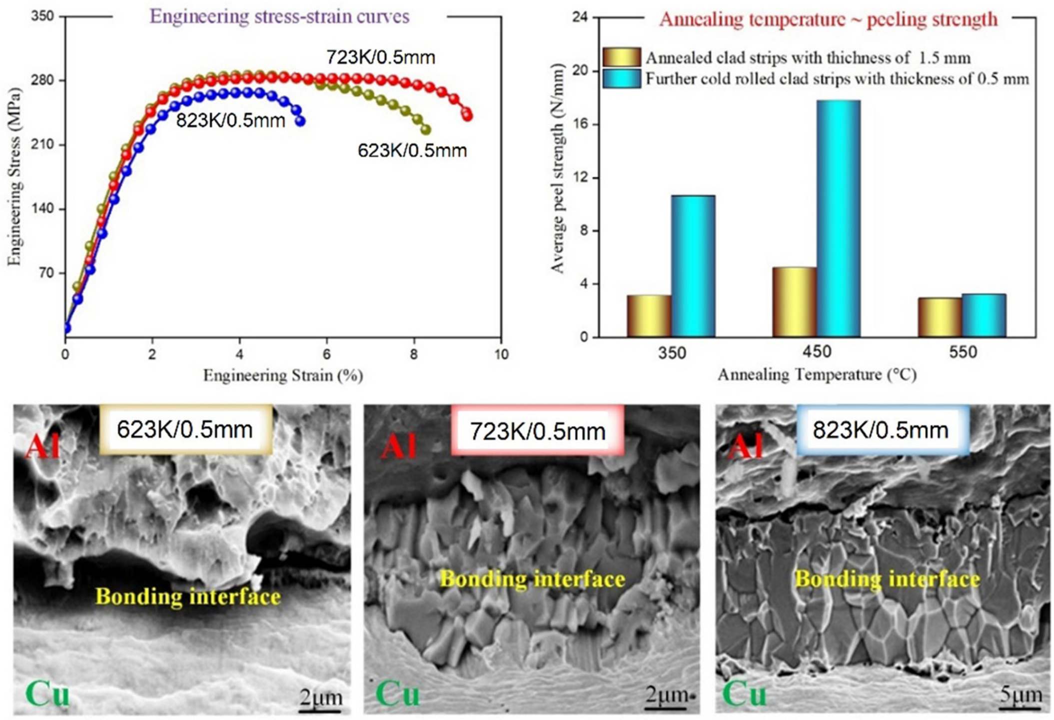

Fig. 13 Effect of interfacial grain size on mechanical performance of Cu/Al clad sheet [88]

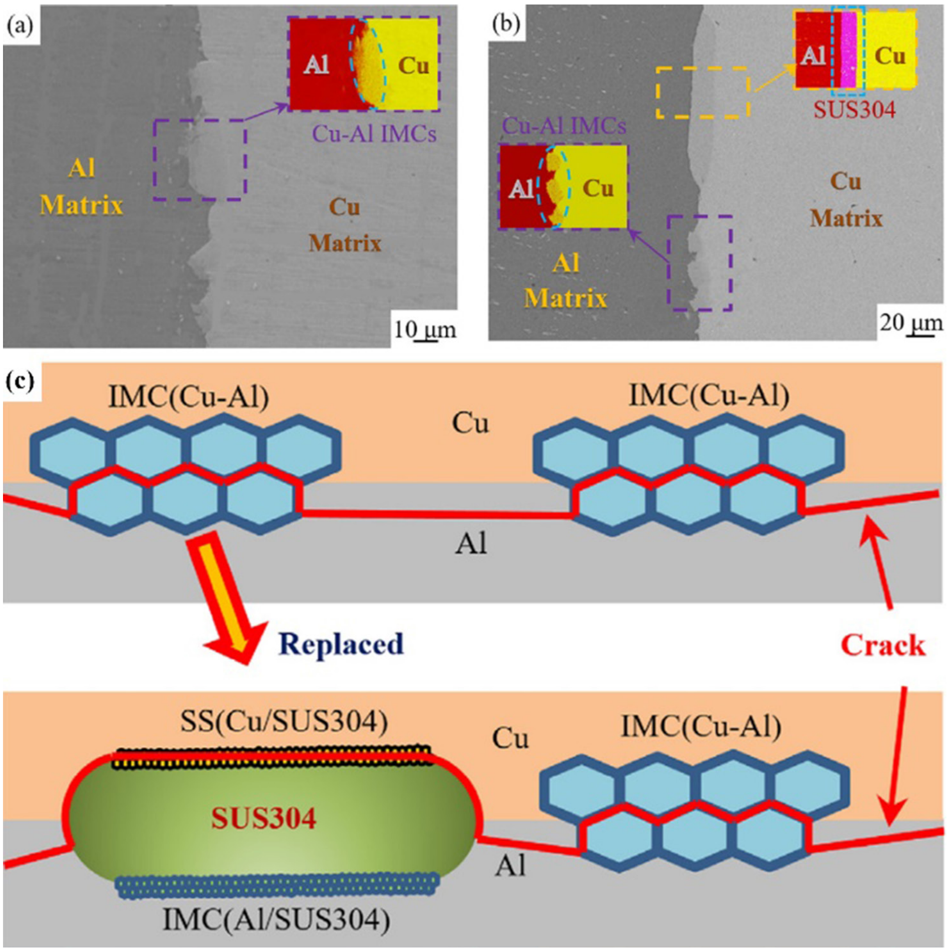

Fig. 14 Effect of SUS304 interlayer on interfacial microstructure and crack propagation path of Cu/Al clad sheet [93]

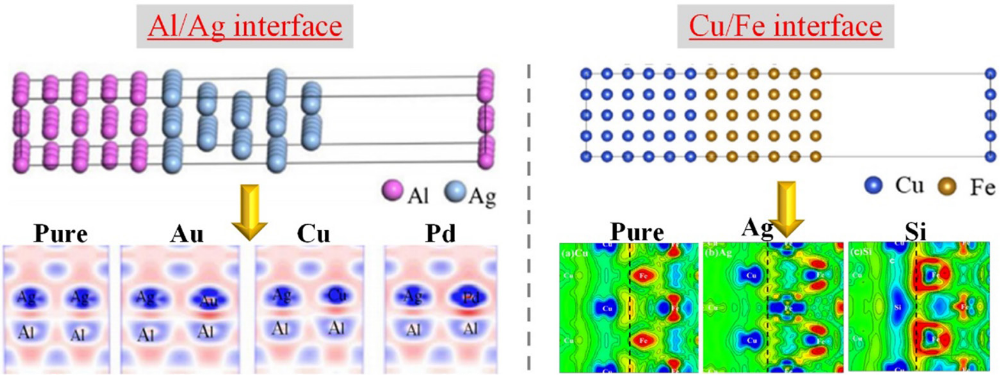

Fig. 15 Promotion mechanism of alloy elements on formation of high-strength covalent bond [97,98]

4.3 Enhancing interfacial shear deformation

In recent years, the influence mechanism of interfacial shear deformation induced by the plastic difference between dissimilar metals in the roll-bonded process on the mechanical performance of metallic composite strip has gained wide interests [101]. In the fabrication process of Al/steel clad sheet, BARUJ et al [102] found that shear deformation could activate the interfacial atoms and promote the formation of high-strength metallic bond, as well as high bonding quality. CHANG et al [103] thought that severe shear deformation formed in the asymmetrical roll bonding of Cu/Al clad sheet could synchronously enhance the mechanic joggle and inhibit the overall collapse of bonding interface. In addition to promoting the formation of high-strength metallic bonding, interfacial shear deformation can also refine the interfacial grains. To enhance the interfacial shear deformation of metallic composite strip, WANG et al [63] explored the corrugated rolling technique. It can significantly refine the interfacial grains and improve the mechanical performance of metallic composite strip. In the fabrication of Mg/Al clad sheet through corrugated rolling technique, they [104] found that interfacial shear deformation could still modify the basal texture of Mg alloy and active the tensile twins, achieving the coordinated deformation of Al and Mg sheets and formation of high-quality bonding interface, as shown in Fig. 16.

4.4 Strengthening interfacial mechanic joggle

According to the results of recent research, strengthening the interfacial mechanic joggle is also an effective method to improve the bonding strength of metallic composite strip. To further improve the bonding strength of Al/Ti/Al clad sheet, cryogenic roll bonding technique was adopted by LIU et al [55]. They concluded that the cryogenic roll bonding process could significantly enhance the interfacial mechanic joggle. Al/steel composite joint with high bonding strength was fabricated by BERGH et al [105] through the continuous extrusion technique. They thought that the microscale mechanic joggle and formation of Al−Fe−Si chemical compound made contributions to the improvement of interfacial bonding quality. QI et al [106] found that widening the interfacial diffusion area and mechanic joggle area was the main way to improve the bonding quality of Ti/Al clad sheet fabricated by the different temperature rolling techniques. HUANG et al [107] indicated that intermetallic compounds formed by the atomic diffusion were broken in the subsequent rolling process and then embedded into the Cu/Al matrix to produce the multiple regions of mechanic joggle and improve the bonding quality. In our previous research [108], the effect of river sand, cement and blast furnace slag as the filling materials on the bending and compressive properties of composite tubes was compared. Results indicated that the excellent mechanical performance could be obtained by the composite tube filled with blast furnace slag. In the rolling and annealing process, the own strength of blast furnace slag was significantly improved by the condensation hardening reaction, and then hard blast furnace slag was embedded into the steel tube to form the large-area mechanic joggle, as shown in Fig. 17.

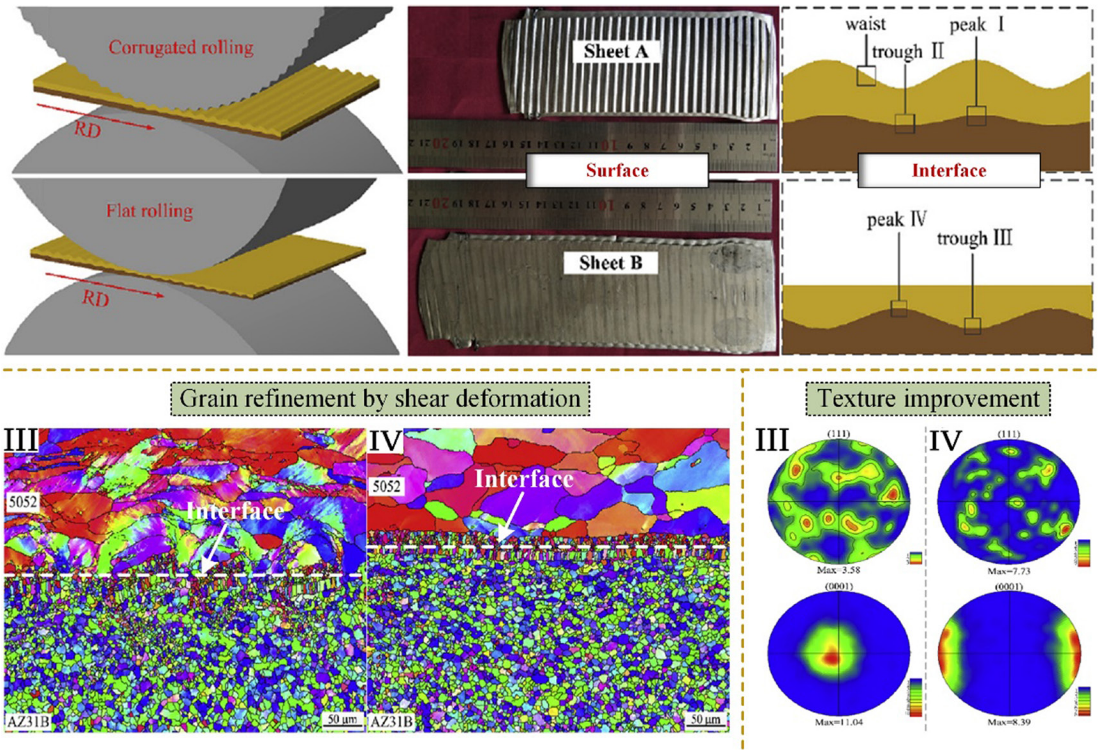

Fig. 16 Promotion mechanism of interfacial shear deformation on grain refinement and texture improvement [104]

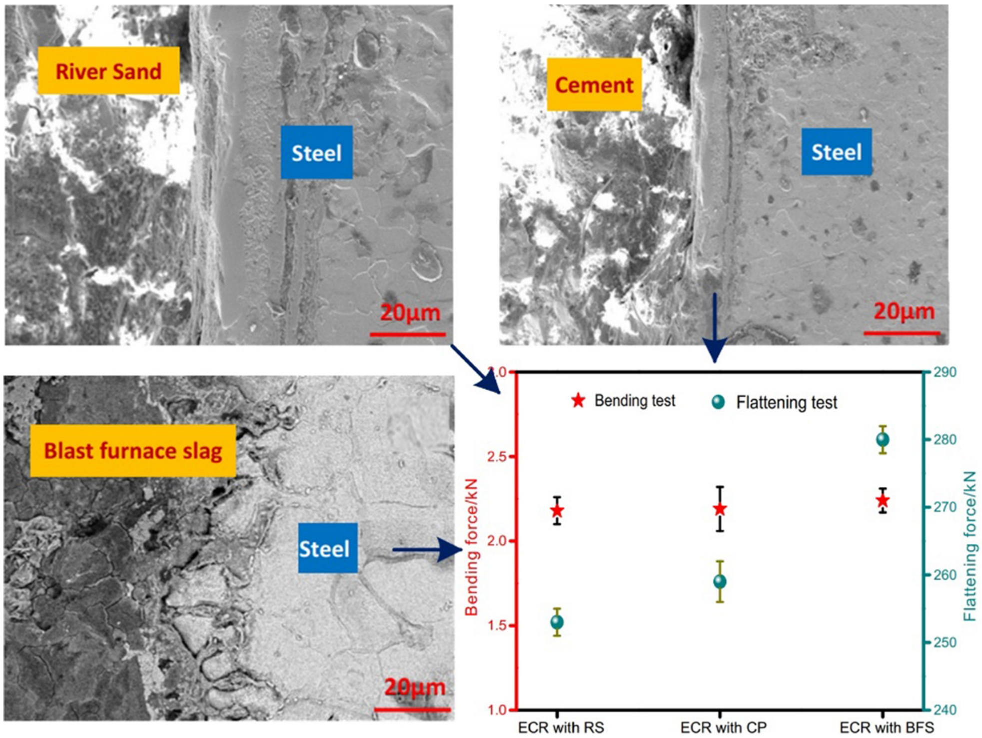

Fig. 17 Effect of interfacial type on mechanical performance of core-filled steel tube [108]

5 Conclusions and prospects

Due to the excellent comprehensive performance of metal laminates, numerous research about the roll bonding techniques, formation mechanism of bonding interface and main factors for the performance improvement of roll-bonded metal laminates has been carried out. Nevertheless, there still exist some sections to improve.

(1) The development of numerical simulation based on finite element method to investigate the deformation of the substrate and cladding metal, as well as the molecular dynamics method to understand the evolution of bonding interface in atomic scale is of great significance.

(2) New roll bonding technique, which can synchronously inhibit the formation of brittle intermetallic compounds, enhancing the interfacial shear deformation and mechanic joggle, demands prompt development. The addition of hard metal interlayer is a promising method. Except for inhibiting the formation of brittle intermetallic compounds, the shear deformation can be induced by the plastic difference between soft matrix and hard metal interlayer. Furthermore, the hard metal interlayer is broken into fragments and embedded into the soft matrix in the roll bonding process, significantly strengthening the mechanic joggle.

(3) As new techniques for the fabrication of metal laminates are emerging in endlessly, the exploration on the more accurate interfacial bonding mechanism is a top priority, which should include the broken of oxidation film, metal plastic flow, microstructure evolution and element diffusion, etc. To obtain the effective regulation method on the interfacial microstructure and mechanical performance of metal laminates, the construction of high accurate model to describe the thickness of substrate and cladding metal in roll bonding process is very necessary.

(4) The development of aided process (i.e. electric field, magnetic field and liquid nitrogen treatment) for the fabrication of metal laminates is vital importance. For these emerging methods, the effect of process parameters and interface bonded conditions on the interfacial microstructure and mechanical performance of metal laminates, as well as the interfacial bonding mechanism, is still needed to be further investigated.

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References

[1] AL-GHAMD K A, HUSSAIN G. Bulging in incremental sheet forming of cold bonded multi-layered Cu clad sheet: Influence of forming conditions and bending [J]. Transactions of Nonferrous Metals Society of China, 2019, 29: 112−122.

[2] KHOJASTEHNEZHAD V M, POURASL H H. Microstructural characterization and mechanical properties of aluminum 6061-T6 plates welded with copper insert plate (Al/Cu/Al) using friction stir welding [J]. Transactions of Nonferrous Metals Society of China, 2018, 28: 415−426.

[3] DING Yun-long, WANG Jian-gang, ZHAO Ming, JU Dong-ying. Effect of annealing temperature on joints of diffusion bonded Mg/Al alloys [J]. Transactions of Nonferrous Metals Society of China, 2018, 28: 251−258.

[4] LI Chun-ling, FAN Ding, YU Xiao-quan, HUANG Jian-kang. Residual stress and welding distortion of Al/steel butt joint by arc-assisted laser welding-brazing [J]. Transactions of Nonferrous Metals Society of China, 2019, 29: 692−700.

[5] NIE Qiang-qiang, CHEN Guo-hong, WANG Bing, YANG Lei, TANG Wen-ming. Process optimization, microstructures and mechanical/thermal properties of Cu/Invar bi-metal matrix composites fabricated by spark plasma sintering [J]. Transactions of Nonferrous Metals Society of China, 2021, 31: 3050−3062.

[6] ZU Guo-yin, WANG Ning, YU Jiu-ming, WEN Jing-lin. Application of composite brazing aluminum foil technology in automotive heat exchanger production [J]. Automobile Technology and Materials, 2003(12): 37−38. (in Chinese)

[7] WANG Xiu-li, WEI Yong-hui. Application and development of metal matrix composites in the aerospace field [J]. Science and Technology Innovation Herald, 2016(6): 16−18. (in Chinese)

[8] CHEN Yu-long. New technology of composite materials for shipbuilding [J]. Fiber Reinforced Plastics/Composites, 1990(3): 17. (in Chinese)

[9] HARTLEY W D, GARCIA D, YODER J K, POCZATEK E, FORSMARK J H, LUCKEY S G, DILLARD D A, YU H Z. Solid-state cladding on thin automotive sheet metals enabled by additive friction stir deposition [J]. Journal of Materials Processing Technology, 2021, 291: 117045.

[10] LIU Bo. Application of copper−steel composites and exothermic welding technology in the grounding system of petrochemical enterprises [J]. China New Technologies and Products, 2011(8): 14. (in Chinese)

[11] WANG Tao, QI Yan-Yang, LIU Jiang-lin, HAN Jian-chao, REN Zhong-kai, HUANG Qing-xue. Research progress of metal laminates roll bonding process at home and abroad [J]. Journal of Harbin Institute of Technology, 2020, 52(6): 42−56. (in Chinese)

[12] XUE Zhi-yong, LIANG He, YU Wan-hua, WU Chun-jing. Orthogonal tests of copper-clad aluminum bimetal continuous casting by nitrogen pressure core-filling [J]. China Foundry, 2013, 10(6): 385−390.

[13] SU Ya-jun, LIU Xin-hua, HUANG Hai-you, LIU Xue-feng, XIE Jian-xin. Interfacial microstructure and bonding strength of copper cladding aluminum rods fabricated by horizontal core-filling continuous casting [J]. Metallurgical and Materials Transactions A, 2011, 42: 4088−4099.

[14] LIU S Y, WANG A Q, LU S J, XIE J P. High-performance Cu/Al laminated composites fabricated by horizontal twin-roll casting [J]. Materialwissenschaft Und Werkstofftechnik, 2018, 49: 1213−1223.

[15] WANG Zhao-jie, LI Yong-wang, ZHANG Wei-na, WANG Guo-dong, LIU Hai-tao. Microstructural evolution and mechanical properties of titanium-alloying high borated steel sheets fabricated by twin-roll strip casting [J]. Materials Science and Engineering A, 2021, 811: 141067.

[16] KIM I K, HONG S I. Effect of heat treatment on the bending behavior of tri-layered Cu/Al/Cu composite plates [J]. Materials and Design, 2013, 47: 590−598.

[17] RHEE K Y, HAN W Y, PARK H J, KIM S S. Fabrication of aluminum/copper clad composite using hot hydrostatic extrusion process and its material characteristics [J]. Materials Science and Engineering A, 2004, 384(1): 70−76.

[18] LOUREIRO A, MENDES R, RIBEIRO J B, LEAL R M, GALVÃO I. Effect of explosive mixture on quality of explosive welds of copper to aluminum [J]. Materials and Design, 2016, 95: 256−267.

[19] YU Yang, SONG Hong-wu, CHEN Yan, XU Yong, ZHANG Shi-hong, WANG Shou-dong. Investigation on fabrication and mechanical property of ultra-thin Cu/Al clad strip used for coax [J]. Materials Science and Technology, 2014, 22(5): 13−18.

[20] SHEN Jian, XIE Shui-sheng, TANG Jing-hui. Dynamic recovery and dynamic recrystallization of 7005 aluminum alloy during hot compression [J]. Acta Metallurgica Sinica (English Letters), 2000, 13(1): 379−386.

[21] HOPPE C, EBBERT C, GROTHE R, SCHMIDT H C, HORDYCH I, HOMBERG W, MAIER H J, GRUNDMEIER G. Influence of the surface and heat treatment on the bond strength of galvanized steel/aluminum composites joined by plastic deformation [J]. Advanced Engineering Materials, 2016, 18(8): 1371−1380.

[22] JING Yu-an, QIN Yi, ZANG Xiao-ming, LI Ying-hong. The bonding properties and interfacial morphologies of clad plate prepared by multiple passes hot rolling in a protective atmosphere [J]. Journal of Materials Processing Technology, 2014, 214(8): 1686−1695.

[23] JING Yu-an, QIN Yi, ZANG Xiao-ming, SHANG Qiu-yue, SONG Hua. A novel reduction-bonding process to fabricate stainless steel clad plate [J]. Journal of Alloys and Compounds, 2014, 617: 688−698.

[24] MENON M, CHEN I W. Bimaterial composites via colloidal rolling techniques: I, Microstructure evolution during rolling [J]. Journal of the American Ceramic Society, 1999, 82:

3413−3421.

[25] ZHANG L, MENG L, ZHOU S P, YANG F T. Behaviors of the interface and matrix for the Ag/Cu bimetallic laminates prepared by roll bonding and diffusion annealing [J]. Materials Science and Engineering A, 2004, 371: 65−71.

[26] PENG X K, WUHRER R, HENESS G, YEUNG W Y. On the interface development and fracture behavior of roll bonded copper/aluminum metal laminates [J]. Journal of Materials Science, 1999, 34: 2029−2038.

[27] LUO Chang-zeng, LIANG Wei, CHEN Zhi-qiang, ZHANG Jian-jun, CHI Cheng-zhong, YANG Fu-qian. Effect of high temperature annealing and subsequent hot rolling on microstructural evolution at the bond-interface of Al/Mg/Al alloy laminated composites [J]. Materials Characterization, 2013, 84: 34−40.

[28] CUI Xi-ping, FAN Guo-hua, GENG Lin, WU Hao, PANG Jin-cheng, GONG Jin-xin. Influence of raw material selection and fabrication parameters on microstructure and properties of micro-laminated TiB_2−TiAl composite sheets [J]. Materials Science and Engineering A, 2014, 589: 83−88.

[29] CHEN Lian-sheng, ZHANG Xin-lei, ZHENG Xiao-ping, SONG Jin-ying, TIAN Ya-qiang. Research status of bimetal laminated composite plate prepared by rolling process [J]. Rare Metal Materials and Engineering, 2018, 47(10): 3243−3250. (in Chinese)

[30] JAMAATI R, TOROGHINEJAD M R. Investigation of the parameters of the cold roll bonding (CRB) process [J]. Materials Science and Engineering A, 2010, 527(9): 2320−2326.

[31] JAMAATI R, TOROGHINEJAD M R. Cold roll bonding bond strengths: Review [J]. Materials Science and Technology, 2011, 27(7): 1101−1108.

[32] CHEN G, LI J T, YU H L, SU L H, XU G M, PAN J S, YOU T, ZHANG G, SUN K M, HE L Z. Investigation on bonding strength of steel/aluminum clad sheet processed by horizontal twin-roll casting, annealing and cold rolling [J]. Materials and Design, 2016, 112: 263−274.

[33] YU H L, LU C, TIEU A K, LI H J, GODBOLE A, KONG C. Annealing effect on microstructure and mechanical properties of Al/Ti/Al laminate sheets [J]. Materials Science and Engineering A, 2016, 660: 195−204.

[34] LUO J G, ACOFF V L. Interfacial reactions of Ti and Al during diffusion welding [J]. Welding Journal, 2000, 79: 239−243.

[35] HWANG W S, WU T I, SUNG W C. Effects of heat treatment on mechanical property and microstructure of aluminum/stainless steel bimetal plate [J]. Journal of Engineering Materials and Technology, 2012, 134(1): 014501.

[36] YANG Yi-hang, LIN Gao-yong, WANG Xiao-ying, CHEN Dian-dian, SUN Ao-kui, WANG De-zhi. Fabrication of Mo-Cu composites by a diffusion-rolling procedure [J]. International Journal of Refractory Metals and Hard Materials, 2014, 43: 121−124.

[37] KIM S H, KANG J H, EUH K, KIM H W. Grain-structure evolution of brazing-treated A4343/A3003/A4343 aluminum brazing sheets rolled with different reductions [J]. Metals and Materials International, 2015, 21: 276−285.

[38] SHENG L Y, YANG F, XI T F, LAI C, YE H Q. Influence of heat treatment on interface of Cu/Al bimetal composite fabricated by cold rolling [J]. Composites (Part B): Engineering, 2011, 42(6): 1468−1473.

[39] SAITO Y, TSUJI N, UTSUNOMIYA H, SAKAI T, HONG R G. Ultra-fine grained bulk aluminum produced by accumulative roll-bonding (ARB) process [J]. Scripta Materialia, 1998, 39: 1221−1227.

[40] WANG Lin, DU Qing-lin, LI Chang, CUI Xiao-hui, ZHAO Xing, YU Hai-liang. Enhanced mechanical properties of lamellar Cu/Al composites processed via high-temperature accumulative roll bonding [J]. Transactions of Nonferrous Metals Society of China, 2019, 29: 1621−1630.

[41] YU H L, LU C, TIEU A K, GODBOLE A, SU L H, SUN Y, LIU M, TANG D L, KONG C. Fabrication of ultra-thin nanostructured bimetallic foils by accumulative roll bonding and asymmetric rolling [J]. Scientific Reports, 2013, 3: 2373.

[42] YU H L, TIEU A K, LU C, GODBOLE A. An investigation of interface bonding of bimetallic foils by combined accumulative roll bonding and asymmetric rolling techniques [J]. Metallurgical and Materials Transactions A, 2014, 45: 4038−4045.

[43] YU H L, LU C, TIEU A K, KONG C. Fabrication of nanostructured aluminum sheets using four-layer accumulative roll bonding [J]. Materials and Manufacturing Processes, 2014, 29(4): 448−453.

[44] SEIFOLLAHZADEH P, ALIZADEH M, ABBASI M R. Strength prediction of multi-layered copper-based composites fabricated by accumulative roll bonding [J]. Transactions of Nonferrous Metals Society of China, 2021, 31: 1729−1739.

[45] ANGHELUS A, AVETTAND-FÈNOËL M, CORDIER C, TAILLARD R. Microstructural evolution of aluminum/Al−Ni−Sm glass forming alloy laminates obtained by controlled accumulative roll bonding [J]. Journal of Alloys and Compounds, 2015, 631: 209−218.

[46] ZENG L F, GAO R, FANG Q F, WANG X P, XIE Z M, MIAO S, HAO T, ZHANG T. High strength and thermal stability of bulk Cu/Ta nanolamellar multilayers fabricated by cross accumulative roll bonding [J]. Acta Materialia, 2016, 110: 341−351.

[47] JAFARIAN H R, MAHDAVIAN M M, SHAMS S A, EIVANI A R. Microstructure analysis and observation of peculiar mechanical properties of Al/Cu/Zn/Ni multi-layered composite produced by accumulative-roll-bonding (ARB) [J]. Materials Science and Engineering A, 2021, 805: 140556.

[48] JIANG S, PENG R L, HEGEDŰS Z, GNÄUPEL-HEROLD T, MOVERARE J J, LIENERT U, FANG F, ZHAO X, ZUO L, JIA N. Micromechanical behavior of multilayered Ti/Nb composites processed by accumulative roll bonding: An in-situ synchrotron X-ray diffraction investigation [J]. Acta Materialia, 2021, 205: 116546.

[49] GAO Rui, JIN Miao-miao, HAN Fei, WANG Bao-ming, WANG Xian-ping, FANG Qian-feng, DONG Yan-hao, SUN Cheng, SHAO Lin, LI Ming-da, LI Ju. Superconducting Cu/Nb nanolaminate by coded accumulative roll bonding and its helium damage characteristics [J]. Acta Materialia, 2020, 197: 212−223.

[50] YU Hai-liang. Progresses in fabrication of high-performance metals by using cryorolling [J]. China Mechanical

Engineering, 2020, 31(1): 89−99. (in Chinese)

[51] WANG Z J, MA M, QIU Z X, ZHANG J X, LIU W C. Microstructure, texture and mechanical properties of AA 1060 aluminum alloy processed by cryogenic accumulative roll bonding [J]. Materials Characterization, 2018, 139: 269−278.

[52] DU Qing-lin, LI Chang, CUI Xiao-hui, KONG C, YU Hai-liang. Fabrication of ultrafine-grained AA1060 sheets via accumulative roll bonding with subsequent cryorolling [J]. Transactions of Nonferrous Metals Society of China, 2021, 31: 3370−3379.

[53] TAKAGAWA Y, TSUJIUCHI Y, WATANABE C, MONZEN R, TSUJI N. Improvement in mechanical properties of a Cu−2.0mass%Ni−0.5mass%Si−0.1mass%Zr alloy by combining both accumulative roll-bonding and cryo-rolling with aging [J]. Materials Transactions, 2013, 54(1): 1−8.

[54] YU Hai-liang, LU Cheng, TIEU K, LI Hai-jun, GODBOLE A, LIU X. Enhanced materials performance of Al/Ti/Al laminate sheets subjected to cryogenic roll bonding [J]. Journal of Materials Research, 2017, 32(19): 3761−3768.

[55] LIU Juan, WU Yu-ze, WANG Lin, WANG Hui, KONG C, PESIN A, ZHILYAEV A P, YU Hai-liang. Fabrication and characterization of high-bonding-strength Al/Ti/Al laminated composites via cryorolling [J]. Acta Metallurgica Sinica (English Letters), 2020, 33: 871−880.

[56] WANG L, LIU J, KONG C, PESIN A, ZHILYAEV A P, YU H L. Sandwich-like Cu/Al/Cu composites fabricated by cryorolling [J]. Advanced Engineering Materials, 2020, 22(10): 2000122.

[57] YANG Q Y, ZHOU Y L, TAN Y B, XIANG S, MA M, ZHAO F. Effects of microstructure, texture evolution and strengthening mechanisms on mechanical properties of 3003 aluminum alloy during cryogenic rolling [J]. Journal of Alloys and Compounds, 2021, 884: 161135.

[58] XIAO Hong, QI Zi-chen, YU Chao, XU Cheng. Preparation and properties for Ti/Al clad plates generated by differential temperature rolling [J]. Journal of Materials Processing Technology, 2017, 249: 285−290.

[59] LI Xiao-bing, ZU Guo-yin, DING Ming-ming, MU Yong-liang, WANG Ping. Interfacial microstructure and mechanical properties of Cu/Al clad sheet fabricated by asymmetrical roll bonding and annealing [J]. Materials Science and Engineering A, 2011, 529: 485−491.

[60] CHEN Xiang, HUANG Guang-sheng, LIU Shuai-shuai, HAN Ting-zhuang, JIANG Bin, TANG Ai-tao, ZHU Yun-tian, PAN Fu-sheng. Grain refinement and mechanical properties of pure aluminum processed by accumulative extrusion bonding [J]. Transactions of Nonferrous Metals Society of China, 2019, 29: 437−447.

[61] SUN Wei, YANG Fei, KONG Fan-tao, WANG Xiao-peng, CHEN Yu-yong. Interface characteristics of Ti6Al4V−TiAl metal-intermetallic laminate (MIL) composites prepared by a novel hot-pack rolling [J]. Materials Characterization, 2018, 144: 173−181.

[62] WANG Long, RUAN Jin-hua. Research on high energy pulse current assisted stainless steel/carbon steel composite [J]. Machinery Design and Manufacture, 2021(8): 207−210. (in Chinese)

[63] WANG Tao, LI Sha, REN Zhong-kai, HAN Jian-chao, HUANG Qing-xue. A novel approach for preparing Cu/Al laminated composite based on corrugated roll [J]. Materials Letters, 2019, 234: 79−82.

[64] BOWDEN F P, TABOR D. The area of contact between stationary and moving surfaces [J]. Proceedings of the Royal Society A, 1939, 169(938): 391−413.

[65] DING Xu-guang, ZHANG Zhi-liang. Solid phase bonding mechanisms and research tendency of bimetals [J]. Forging and Stamping Technology, 1997(4): 32−36. (in Chinese)

[66] MOHAMED H A, WASHBURN J. Mechanism of solid state pressure welding [J]. Welding Journal, 1975, 54(9): 302−310.

[67] MITANI Y, VARGAS R, ZAVALA M. Deformation and diffusion bonding of aluminide coated steels [J]. Thin Solid Films, 1984, 111(1): 37−42.

[68] VAIDYANATH L R, NICHOLAS M G, MILNER D R. Pressure welding by rolling [J]. British Welding Journal, 1959, 6: 13−28.

[69] YU Jiu-ming, YU Chang-sheng, ZHU Quan. Effect of rolling temperature on bonding strength of clad plates [J]. Journal of Northeastern University (Natural Science), 1995, 16(5): 491−494. (in Chinese)

[70] PARKS J M. Recrystallization in welding [J]. Welding Journal, 1953, 32(5): 209−221.

[71] ZU Guo-yin. Theories and technologies of preparation layered metal composite [M]. Shenyang: Northeastern University Press, 2013: 17. (in Chinese)

[72] BAY N. Cold welding. Part 1: Characteristics, bonding mechanisms, bond strength [J]. Metal Construction, 1986(7): 369−372.

[73] KHALEDI K, BREPOLS T, REESE S. A multiscale description of bond formation in cold roll bonding considering periodic cracking of thin surface films [J]. Mechanics of Materials, 2019, 137: 103142.

[74] NIE Hui-hui, ZHENG Liu-wei, KANG Xiao-ping, HAO Xin-wei, LI Xian-rong, LIANG Wei. In-situ investigation of deformation behavior and fracture forms of Ti/Al/Mg/Al/Ti laminates [J]. Transactions of Nonferrous Metals Society of China, 2021, 31: 1656−1664.

[75] LI Yong-wang, WANG Zhao-jie, FU Dao-gui, LI Gang, LIU Hai-tao, ZHANG Xiao-ming. Fabrication of high borated austenitic stainless steel thick plates with enhanced ductility and toughness using a hot-roll-bonding method [J]. Materials Science and Engineering A, 2021, 799: 140212.

[76] FERNANDEZ J M, ASTHANA R, SINGH M, VALERA F M. Active metal brazing of silicon nitride ceramics using a Cu-based alloy and refractory metal interlayers [J]. Ceramics International, 2016, 42: 5447−5454.

[77] WU Bo, LI Long, XIA Cheng-dong, GUO Xiao-feng, ZHOU De-jing. Effect of surface nitriding treatment in a steel plate on the interfacial bonding strength of the aluminum/steel clad sheets by the cold roll bonding process [J]. Materials Science and Engineering A, 2017, 682: 270−278.

[78] ZHANG W, BAY N. Cold welding: experimental investigation of the surface preparation methods [J]. Welding Journal, 1997, 76: 326−330.

[79] JAMAATI R, TOROGHINEJAD M R. Effect of friction, annealing conditions and hardness on the bond strength of Al/Al strips produced by cold roll bonding process [J].

Materials and Design, 2010, 31: 4508−4513.

[80] YU H L, TIEU A K, LU C, LIU X, GODBOLE A, LI H J, KONG C, QIN Q H. A deformation mechanism of hard metal surrounded by soft metal during roll forming [J]. Scientific Reports, 2014, 4: 5017.

[81] ROY S, NATARAJ B R, SUWAS S, KUMAR S, CHATTOPADHYAY K. Accumulative roll bonding of aluminum alloys 2219/5086 laminates: Microstructural evolution and tensile properties [J]. Materials and Design, 2012, 36: 529−539.

[82] HUMPHREYS F J. A unified theory of recovery, recrystallization and grain growth, based on the stability and growth of cellular microstructures—II. The effect of second-phase particles [J]. Acta Materialia, 1997, 45: 5031−5039.

[83] XU Ze-bing, LIU Man-ping, JIA Zhi-hong, ROVEN H J. Effect of cryorolling on microstructure and mechanical properties of a peak-aged AA6082 extrusion [J]. Journal of Alloys and Compounds, 2017, 695: 827−840.

[84] POZUELO M, CARREÑO F, CEPEDA-JIMÉNEZ C M, RUANO O A. Effect of hot rolling on bonding characteristics and impact behavior of a laminated composite material based on UHCS-1.35 pct C [J]. Metallurgical and Materials Transactions A, 2008, 39: 666−671.

[85] PENG X K, HENESS G, YEUNG W Y. Effect of rolling temperature on interface and bond strength development of roll bonded copper/aluminum metal laminates [J]. Journal of Materials Science, 1999, 34: 277−281.

[86] MALEKI H, BAGHERZADEH S, MOLLAEI-DARIANI B, ABRINIA K. Analysis of bonding behavior and critical reduction of two-layer strips in clad cold rolling process [J]. Journal of Materials Engineering and Performance, 2013, 22: 917−925.

[87] MAO Zhi-ping, XIE Jing-pei, WANG Ai-qin, WANG Wen-yan, MA Dou-qin, LIU Pei. Effects of annealing temperature on the interfacial microstructure and bonding strength of Cu/Al clad sheets produced by twin-roll casting and rolling [J]. Journal of Materials Processing Technology, 2020, 285: 116804.

[88] GAO Hai-tao, LIU Xiang-hua, QI Jun-long, AI Zheng-rong, LIU Li-zhong. Microstructure and mechanical properties of Cu/Al/Cu clad strip processed by the powder-in-tube method [J]. Journal of Materials Processing Technology, 2018, 251: 1−11.

[89] GAO Hai-tao, LIU Xiang-hua, AI Zheng-rong, ZHANG Shi-long, LIU Li-zhong. Strengthening effect of reduced graphene oxide in steel clad copper rod [J]. Applied Physics A, 2016, 122(11): 981.

[90] LEE S, SON I S, LEE J K, LEE J S, KIM Y B, LEE G A, LEE S P, CHO Y R, BAE D S. Effect of aging treatment on bonding interface properties of hot-pressed Cu/Al clad material [J]. International Journal of Precision Engineering and Manufacturing, 2015, 16: 525−530.

[91] AKCA E, GURSEL A. The importance of interlayers in diffusion welding—A review [J]. Periodicals of Engineering and Natural Sciences, 2015, 3(2): 12−16.

[92] KIM H J, HONG S I. Effect of Ni interlayer on the interface toughening and thermal stability of Cu/Al/Cu clad composites [J]. Metals and Materials International, 2019, 25: 94−104.

[93] GAO Hai-tao, WANG Lin, LIU Shi-lei, LI Jing, KONG C, YU Hai-liang. Effects of a stainless steel interlayer on the interfacial microstructure and bonding strength of Cu/Al clad sheets prepared via the powder-in-tube method [J]. Journal of Materials Research and Technology, 2021, 15: 3514−3524.

[94] YAN J C, ZHAO D S, WANG C W, WANG L Y, WANG Y, YANG S Q. Vacuum hot roll bonding of titanium alloy and stainless steel using nickel interlayer [J]. Materials Science and Technology, 2009, 25(7): 914−918.

[95] LUO Zong-an, WANG Guang-lei, XIE Guang-ming, WANG Li-peng, ZHAO Kun. Interfacial microstructure and properties of a vacuum hot roll-bonded titanium stainless steel clad plate with a niobium interlayer [J]. Acta Metallurgica Sinica (English Letters), 2013, 26(6): 754−760.

[96] VARMAZYAR J, KHODAEI M. Diffusion bonding of aluminum-magnesium using cold rolled copper interlayer [J]. Journal of Alloys and Compounds, 2019, 773: 838−843.

[97] PENG C, LIANG S, HUANG F X, ZENG L J, ZHOU L, RAN X J. Influence of Au, Cu, Pd added in Ag alloy on stability and electronic structure of Ag/Al interface by first-principles calculations [J]. Materials Today Communications, 2020, 22: 100670.

[98] WANG Y F, LI M, GAO H Y, WANG J, SUN B D. First-principles study on the Cu/Fe interface properties of ternary Cu−Fe−X alloys [J]. Materials, 2020, 13(14): 3112.

[99] YUAN Z P, TU Y Y, YUAN T, ZHANG Y H, HUANG Y H. Effect of post-brazing heat treatment on the corrosion mechanism of sandwich multi-layered aluminum sheets [J]. Vacuum, 2021, 183: 109781.

[100] CZELEJ K, KURZYDŁOWSKI K J. Ab initio prediction of strong interfacial bonding in the Fe/Al bimetallic composite system [J]. Scripta Materialia, 2020, 177: 162−165.

[101] QI Jun-long, LIU Xiang-hua, GAO Hai-tao, CHEN Jing-qi, HU Xian-lei, YAN Shu. Experiment and analytical model based on slab method for drawing process of core filled tube [J]. International Journal of Mechanical Sciences, 2020, 165: 105152.

[102] BARUJ H D, SHADKAM A, KAZEMINEZHAD M. Effect of severe plastic deformation on evolution of intermetallic layer and mechanical properties of cold roll bonded Al-steel bilayer sheets [J]. Journal of Materials Research and Technology, 2020, 9(5): 11497−11508.

[103] CHANG Dong-xu, WANG Ping, ZHAO Ying-ying. Interfacial reaction and strengthening mechanism of Cu/Al composite strip produced by asymmetrical rolling [J]. Journal of Northeastern University (Natural Science), 2019, 40(11): 1574−1578, 1583. (in Chinese)

[104] WANG Tao, WANG Yue-lin, BIAN Li-ping, HUANG Qing-xue. Microstructural evolution and mechanical behavior of Mg/Al laminated composite sheet by novel corrugated rolling and flat rolling [J]. Materials Science and Engineering A, 2019, 765: 138318.

[105] BERGH T, SANDNES L, JOHNSTONE D N, GRONG Ø, BERTO F, HOLMESTAD R, MIDGLEY P A, VULLUM P E. Microstructural and mechanical characterization of a second generation hybrid metal extrusion & bonding aluminum-steel butt joint [J]. Materials Characterization, 2021, 175: 110761.

[106] QI Zi-chen, XIAO Hong, YU Chao, XU Peng-peng, WU Zong-he, ZHAO Yun-peng. Preparation, microstructure and mechanical properties of CP-Ti/AA6061-Al laminated composites by differential temperature rolling with induction heating [J]. Journal of Manufacturing Processes, 2019, 44: 133−144.
[107] HUANG Hua-gui, DONG Yi-kang, YAN Meng, DU Feng-shan. Evolution of bonding interface in solid–liquid cast–rolling bonding of Cu/Al clad strip [J]. Transactions of Nonferrous Metals Society of China, 2017, 27: 1019−1025.
[108] GAO Hai-tao, LIU Xiang-hua, QI Jun-long, AI Zheng-rong. Preparation and characterization of novel energy-saving composite rod [J]. Construction and Building Materials, 2019, 207: 592−599.

轧制(热轧，冷轧，深冷轧制)复合法制备轻质金属层状带材研究进展

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摘　要：由于兼具多种材料的综合优势，金属层状复合板得到了广泛关注。轧制复合法具有可稳定连续生产的优势，已成为目前制备金属层状复合板的主要方法之一。本文介绍轧制复合金属层状复合板的研究进展，主要包括热轧复合法、冷轧复合法、累积叠轧法和深冷轧制复合法。系统地讨论金属层状复合板的界面形成机理及影响界面结合质量的主要因素，并对高性能金属层状复合板未来发展方向提出指导性的展望。

关键词：金属层状复合板；轧制复合法；结合界面；力学性能

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